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UF_6 Release Leak Hazard Analyses

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Signature

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Commentary? 1986

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UF_6 LEAK HAZARD ANALYSIS

This document has been approved for release to the public by:

David G. Gilliland 5/15/95
Asst. Technical Information Officer Date
Oak Ridge K-25 Site

Oak Ridge K-25 Site
Oak Ridge, Tennessee 37831-7314
managed by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the U.S. DEPARTMENT OF ENERGY
under Contract DE-AC05-84OR21400

ABSTRACT

The potential for a large UF_6 release at ORGDP is greatest where cylinders of the hot liquid are handled. Calculations of gas release rates resulting from broken or open cylinder valves in the six o'clock and 12 o'clock positions are shown. The great density of UF_6 gas and solids fallout make the standard meteorological formulae for computation of downwind concentrations inapplicable; however, it is shown that the hazard to personnel downwind from a large UF_6 leak can be approximated for emergency planning purposes by calculating the HF concentrations produced by reaction of the UF_6 with atmospheric and respiratory tract moisture. Action points and appropriate action are defined for minimizing personnel exposure hazards. Emergency procedures based on this analysis of the hazards have been written.

Subsequent studies override this statement

SUMMARY AND CONCLUSIONS

If a valve positioned below the liquid level of UF_6 in a cylinder breaks off, all of the liquid down to the level of the valve will be expelled so quickly and forcefully that it would be impractical and unsafe to try to plug off the flow of hot liquid. Even for small liquid leaks the most practical approach might be to attempt to tilt or roll the cylinder to bring the opening above the liquid level and then attempt to stop the gas leak.

There is enough volume in each of our UF_6 cylinder handling buildings to contain all of the gas which would flash from any cylinder leak of liquid or gaseous UF_6. Venting capacity at or near roof level for HF and displaced air in case of high pressure expulsion of UF_6 liquid may need engineering study. Steam, rather than water, should be used to precipitate UO_2F_2 for vacuum recovery inside a building.

There should be adequate time to dress out an emergency crew in complete protective clothing and self-contained breathing equipment to safely plug off a gas leak from a broken off valve in the 12 o'clock position before a ton of the gas has escaped from the cylinder. Visibility will be the chief problem inside a building filled with dense white fog. With adequate thermal protection the men can be guided by the sound and feel of escaping gas. They can stop the leak by pressing and securing an insulated patch against the opening or driving a wooden plug into it.

Dry ice may be used on a leaky cylinder to reduce the vapor pressure, but the use of water should be avoided. A possible exception would be to use water spray to knock down gas escaping from a leak out-of-doors to reduce the hazard to personnel downwind. Care must be used never to introduce a stream of water into a cylinder of enriched UF_6.

The visible cloud and strong smell of HF from a big UF_6 leak will be the best guides for downwind personnel protection. People inside downwind buildings should shut down the ventilation and stay inside rather than evacuate into high concentrations of gas.

UF_6 RELEASE

Duncan, per your request, Ted

Evaluation of the Hazard

Exposure to UF_6 and its reaction products in the atmosphere can harm people in several different ways. Uranium, like lead and mercury, is a heavy metal poison to internal body organs; but unlike lead and mercury, uranium is also radioactive and emits alpha particles inside the body where resistance to their ionizing effect is low. The fluorides accompanying a release are also toxic. At ORGDP, where enrichment in the more radioactive isotopes of uranium is low, kidney damage due to chemical poisoning is the chief danger from chronic inhalation of low concentrations. In higher concentrations chemical burns, especially to respiratory mucous membranes, can be most damaging, causing pulmonary edema to personnel without respiratory protection. The use of water to combat a release of enriched UF_6 could possibly cause moderation in unsafe geometry to initiate a nuclear criticality where penetrating radiation would be the hazard.

Inhalation by personnel without respiratory protection presents the greatest potential hazard to the greatest number of people. The greater the amount and rate of release, the harder to confine and the farther downwind that dangerous--even lethal--concentrations can be carried. The potential for the greatest amount and highest rate of release exists when UF_6 in large cylinders is in the liquid phase with vapor pressure above atmospheric pressure. This condition exists in K-1131 feed and tails, K-413 product withdrawal and K-1423 toll enrichment facilities.

Cylinders at these three facilities contain two, ten or fourteen tons of UF_6, and liquid is transferred to or from the cylinders in these buildings. If the valve on a cylinder of liquid UF_6 were opened wide or failed with the valve at the bottom--six o'clock position--vapor pressure on the surface of the liquid in the cylinder could discharge most of the contents to atmosphere in a few minutes time, and under adverse weather conditions lethal concentrations could be carried several miles downwind, if the gas were not contained by the building. However, if the cylinder valve were at the top--twelve o'clock position--evaporation of liquid to feed the leak would self-cool and freeze the liquid and much of the UF_6 could be contained in the cylinder. With the valve in the 12 o'clock position, it would be feasible for properly protected operators and emergency squad personnel to drive one of the specially fabricated wood plugs into the opening and stop the leak.

Plantwide and Offsite Effects of a Large UF_6 Leak

The usual formulae for calculating the downwind concentration of atmospheric pollutants based on release rate and meteorological conditions cannot be realistically applied to releases of UF_6 gas due to its high density and the fallout of solids.

At an AICHE symposium in November, 1972, F. T. Bodurtha[1] reporting on the behavior of gases 1.5 to 5 times the density of air stated, "Previously existing atmospheric dispersion equations cannot be used with reliability to estimate the concentration of dense stack gases at the ground." Since UF_6 gas is more than twice as dense as the most dense gas noted in Bodurtha's report, its deviation from the norm should be even greater. Due to its great density and tendency to hug the ground much of the UF_6 gas could be trapped behind buildings or hills before reaching a point of interest downwind.

Experience with accidental UF_6 gas releases plus limited experiments where known amounts have been deliberately released to the atmosphere prove that there is always a considerable amount of fallout of solids from a UF_6 gas release to atmosphere. Since the vapor pressure of solid UF_6 is atmospheric at about 133°F some solid UF_6 will precipitate from pockets of undiluted UF_6 gas in the atmosphere, especially in cold weather. However, the moisture in atmospheric air will react readily with both gaseous and particulate UF_6 so that the end product of fallout material is UO_2F_2.

The reaction of UF_6 with water vapor in the air proceeds according to the formula: $UF_6 + 2H_2O \rightarrow UO_2F_2 + 4HF$. It can be seen therefore that 352 pounds of UF_6 when completely reacted with water produces 238 pounds of uranium as uranyl fluoride and 80 pounds of HF. Although the HF produced weighs nearly 23 percent as much as the reacted UF_6 it occupies 4 times the volume and therefore is less than 6 percent as dense. Therefore the HF, even after it hydrolyzes to form the characteristic white cloud or plume, is light enough to remain air-borne and to be dispersed more nearly in conformance with the usual formulae for calculating concentrations of atmospheric pollutants.

As a result of these considerations the public emergency limit (PEL) was set by the committee at 8 mg/m^3 for ten minutes or 4 mg/m^3 for exposures lasting thirty minutes to an hour. The Committee had previously set 8 mg/m^3 for 30 minutes or 16 mg/m^3 for 10 minutes as emergency exposure limits applicable only to military and space operations.[4]

Since the odor of HF is detectable at concentrations well below the 4 mg/m^3 judged to be safe for public exposure, and a burning sensation in the nose is produced by 10 mg/m^3 which is close to the ten minute exposure limit judged to be safe for the public, a good conservative rule-of-thumb for protecting personnel would be to get them out of the path of a visible contaminant cloud before the smell of HF becomes strong and acrid. But people must not be evacuated from the relative safety of building atmosphere into a visible cloud of HF where a few breaths could prove fatal.

It may now prove helpful for emergency planning to see how far downwind concentrations of HF in excess of the PEL values might be carried from a large UF_6 release. The AEC publication, Meteorology and Atomic Energy - 1968 gives the formula $Q = X \pi \sigma y \sigma z \bar{u}$ for relating downwind concentrations with release rate in grams per second. X is the downwind concentration at ground level on the center line of the cloud plume in grams per cubic meter. π is 3.14. $\bar{u}$ is wind velocity in meters per second. σy and σz in meters are the atmospheric dispersion coefficients crosswind and vertical respectively. Values for σy and σz increase with decreasing atmospheric stability and with distance from the leak source. Values for σy and σz for problem solving may be obtained from graphs in the AEC book for Pasquill's six meteorological categories A through F in the order of increasing atmospheric stability.

For brevity we will consider two UF_6 leak rates under two meteorological categories. The most unfavorable category F occurs during temperature inversions on clear nights with wind velocities less than 5 miles per hour (2 m/sec). Category D prevails during cloudy weather day or night with wind velocities 12 to 15 miles per hour (6 m/sec). The chapter on UF_6 leak rates in this report shows if a valve in the 12 o'clock position were broken off a hot 14-ton cylinder the leak rate might be 70 pounds per minute or 530 g/sec UF_6 gas, equivalent to 122 g/sec of HF. At the 6 o'clock position UF_6 gas might be released at a 1070 pound per minute rate equivalent to 1840 g/sec of HF.

There is another good reason for considering the HF rather than UF_6 gas in analyzing the hazard from a big UF_6 gas release besides the applicability of meteorological formulae. The HF, breathed into the lungs of man, whether generated by UF_6 reaction with moisture in the air or in the respiratory tract itself is probably more damaging than the intake of uranium when the exposure is a single massive dose. That is to say that pulmonary edema induced by irritation of the respiratory mucosa is more likely and dangerous than kidney damage or irradiation in the lungs if a man downwind from a large UF_6 release inhales an overdose of the contaminants. This is most apparent if the exposure is far downwind after a large share of the uranium has fallen out of the contaminant cloud. The following incident shows that it may also be true of exposures very near the source where the contaminant breathed is more likely to be UF_6 gas.

The clinical aspects of an operator's exposure to a UF_6 release when he inadvertently unscrewed the valve from a hot 10-ton cylinder has been reported.[2] The operator was hospitalized with pulmonary edema. And, although a total of 3.65 milligrams of uranium were recovered from his urine, there were no signs of blood or albumin or any other evidence of kidney damage. Assuming that 3.65 mg U was the total absorbed dose and that this represents the usual 25 percent retention he would have inhaled 14.6 mg U equivalent to 21.6 mg UF_6 which could generate 5 mg HF. If we assume a two minute exposure and an accelerated breathing rate of .025 m^3 per minute the HF concentration would have been 5/.050 or 100 mg/m^3 which the National Research Council[3] has described as intolerable for more than a minute, and certainly in the range to irritate the respiratory system.

The following excerpts from a 1971 publication[3] by a committee of the Nationa Research Council should help if we are to use HF concentrations to estimate danger to personnel downwind from a big UF_6 release: "An individual exposed to more than 10 mg/m^3 will almost immediately experience a biting or burning sensation in the nose, followed by a nasal discharge ... at 26 mg/m^3 for three minutes he (man) is uncomfortable and able to taste the gas; at 50 mg/m^3 the severity of the irritation increases; and at 100 mg/m^3 a stinging sensation of the skin is added and other irritations are so severe as to make exposure for more than one minute intolerable ... Since the primary irritant action of HF is on the mucosa, particularly the respiratory mucosa, it is important to recognize the more sensitive segments of the population, e.g., the asthmatics and bronchitics, as the limiting factors."

Substituting the half hour PEL value of .004 g/m^3 for X in the formula we would have, for the 12 o'clock positioned valve break, under category F conditions: $122 = .004 \times 3 \times 2 \times \sigma y \sigma z$ or $\sigma y \sigma z = 5000$. From the graph we find $\sigma y \sigma z = 5000$ at 5×10^3m or approximately 3.1 miles from the source. When the 10-minute PEL value .008 g/m^3 is substituted for X under the same conditions $\sigma y \sigma z = 2500$ at 3×10^3m or approximately 1.9 miles from the source. Since there are offsite homes approximately 1.7 miles north of the buildings where hot UF_6 cylinders are handled there might appear at first glance to be some danger there if such a leak as the one described were allowed to escape to the outdoor atmosphere at night under category F conditions. However, a careful appraisal of all the pertinent facts indicate negligible danger in offsite homes from such a release. The concentration values are center line of plume maximum averages. The wind would have to be so directionally steady as to keep the plume centered on one home for at least ten minutes for a person standing outside to get a dose of HF which the NRC committee says is still safe. Actually the wind at ORGDP under nighttime category F conditions fluctuates directionally from a generally NE to SW direction where the nearest offsite home is more than two miles away. Since dispersion is greater under other meteorological categories, we must conclude that a 12 o'clock positioned UF_6 cylinder valve break in ORGDP will not endanger personnel in offsite homes.

For the 6 o'clock positioned valve break the contents of the cylinder are exhausted in about 15 minutes so the half hour PEL may be ignored. Substituting the .008 mg/m^3 10 minute PEL value in the formula we have $1840 = .008 \times 3 \times 2 \times \sigma y \sigma z$ or $\sigma y \sigma z = 38000$, which on the F category scale occurs at about 24×10^3M or 15 miles from the source. Even the 100 mg/m^3 concentration, said to be intolerable for more than a minute, could be carried nearly two miles downwind under the very adverse weather conditions. Under Class D, cloudy weather condition, with a 6m/sec. wind velocity, the formula gives $1840 = .008 \times 3 \times 6 \times \sigma y \sigma z$ or $\sigma y \sigma z = 12{,}800$ and the distance on the D scale is 3×10^3M or 1.9 miles. All of which adds up to the fact that such a leak out-of-doors could have extremely serious and extensive offsite effects under very adverse weather conditions and very little or no effect under slightly more favorable weather conditions.

Use of the dispersion formula for HF to interpret UF_6 gas behavior has most serious limitations when applied to onsite effects of a 6 o'clock positioned valve break. Shortage of space, time, humidity and mixing action to complete the UF_6 reaction to produce HF could allow a large mass of dense UF_6 to travel low over the ground to reach nearby buildings.

Tables 1 and 2 give formula results and the "Remarks" column suggests some emergency actions which would have to be based more on the actual cloud plume behavior than theoretical values.

TABLE 1

Hot UF_6 Cylinder valve in 12 o'clock position broken off in K-1423 storage lot.

Downwind Building	Distance Km for formula	Weather	Wind $\underline{U}$	Time min.	Equation $X = \frac{122g./sec}{3}$	Max. HF Conc. = Mg/m^3	Remarks
K-1001 & K-1007	2/3 mile or 1 km	F Category usual clear night time inversion	2m/sec or 4.5mph	8	$X = \frac{122}{6x28x14}$	52	Many buildings stand between K-1423 and K-1[illegible] to make the $52mg/m^3$ a higher than realistic valu[illegible] But unreacted and relatively undiluted UF_6 might [illegible] swept from K-1423 east lot into the lower elevati[illegible] around K-1007. Evacuate K-1007 into vehicles an[illegible] drive out of gas path; the 8 minutes gives time.
Same	"	D-Neutral cloudy day or night	6m/sec or 13.5mph	3	$X = \frac{122}{18x70x30}$	3	No time to evacuate for D category. Shut off ve[illegible] lation and use building as temporary refuge. Rea[illegible] no danger at K-1001.
K-1401 North	1/7mi. 0.23km	F	2m/sec	2	$X = \frac{122}{6x9x3}$	750	Personnel stay inside building and go to sou[illegible] end; carry available [illegible]sault masks and respirator[illegible] If odor inside K-1401 South gets strong, watch fo[illegible] opportunity or hold breath and dash across 10th S[illegible] into K-1008. Mobilize buses and carry alls with masked drivers to transport personnel from K-1401 K-1008 to safer location.
Same		D	6m/sec	0.6	$X = \frac{122}{18x18x10}$	40	Ditto above - may be unreacted, undiluted UF_6.
K-1036N	1/10mi 0.16km	F	2	1.3	$X = \frac{122}{6x4x1.2}$	4236	Stay inside building and go to south end. C[illegible] available gas masks. Dash across street to K-103[illegible] K-1401 as appropriate to cloud movement. Transpo[illegible] to safety location.
Same		D	6	0.4	$X = \frac{122}{18x12x6.5}$	87	Ditto above - may be unreacted, undiluted UF_6.
K-1035	1/5mi 0.32km	F	2	2.6	$X = \frac{122}{6x12x5}$	339	Go to east side of building and use mask, wa[illegible] for street to clear or hold breath and dash acros[illegible] street into K-1401.
Same		D	6	0.8	$X = \frac{122}{18x25x14}$	20	
K-303-7	0.23km	F	2	2	$X = \frac{122}{6x9x3}$	750	Shut all doors and windows east end of build[illegible] especially basement doors. Not necessary to shut[illegible] ventilation unless odor becomes detectable. Stay[illegible] operating floor and move out of area with HF odor[illegible] Note K-25 and K-27 buildings unventilated areas m[illegible] excellent shelters and escape routes.
		D	6	0.6	$X = \frac{122}{18x18x6.5}$	40	
Nearest Offsite Home	1.7mi 2.75km	F	2	23	$X = \frac{122}{6x90x27}$	8	No danger in homes. Odorous outside. There[illegible] time to investigate and make sure.
		D	6	8	$X = \frac{122}{18x180x65}$	0.6	

Hot UF_6 Cylinder Valve in 6 o'clock position broken off in K-1423 storage lot.

Downwind Building	Distance Km	Weather Category	Wind $\bar{U}$ m/sec	Time min.	Equation Max. HF Conc. $X = \frac{1840 g/sec}{3}$ = Mg/m^3	Remarks
K-1001 & K-1007	1	F	2	8	$X = \frac{1840}{6x28x14} = 782$	This cannot happen because cylinders in the 1[illegible] are always handled with valves in the 12 o'clock position. The table is to show comparative serious[illegible] ness of a liquid UF_6 leak. Evacuate K-1007 and K-1001 and get the people into vehicles and safely out of the plant if there [illegible] time. Otherwise take cover in the buildings and evacuate when it is safe to do so, or when respira[illegible] protection can be provided.
		D	6	3	$X = \frac{1840}{18x70x30} = 49$	
K-1401 N	0.23	F	2	2	$X = \frac{1840}{6x9x3} = 11358$	Any plant building downwind could have HF conc[illegible] trations in the atmosphere immediately outside too dangerous to breathe as the equations show. The u[illegible] wind side of buildings in the unobstructed path of release may have much higher concentrations due to unreacted, undispersed UF_6 gas. The downwind side o[illegible] buildings and buildings shielded by other buildings may have much lower concentrations. The UF_6 release lasts 15 minutes but contact with water vapor to co[illegible] plete HF generation could take considerably longer. Get people out of near buildings by clean paths in[illegible] safer places before cloud plume spreads to blanket buildings and streets.
		D	6	.6	$X = \frac{1840}{18x18x10} = 568$	
K-1036N	0.16	F	2	1.3	$X = \frac{1840}{6x4x1.2} = 63889$	
		D	6	0.4	$X = \frac{1840}{18x12x6.5} = 1310$	
K-1035	0.32	F	2	2.6	$X = \frac{1840}{6x12x5} = 5112$	
		D	6	0.8	$X = \frac{1840}{18x25x14} = 292$	
K-303-7	0.23	F	2	2	$X = \frac{1840}{6x9x3} = 11358$	
		D	6	.6	$X = \frac{1840}{18x18x10} = 568$	
Offsite Home North of Plant	2.75	F	2	23	$X = \frac{1840}{6x90x27} = 126$	Request AEC patrol to obtain help from local law officers to alert and/or evacuate offsite home[illegible] downwind and within two or three miles of the plan[illegible] The plant emergency director and emergency sq[illegible] men, guided chiefly by observation of the visible contaminant cloud plume, will take appropriate act[illegible] in the offsite area until relieved of this respon- sibility by AEC or local law officials.
		D	6	8	$X = \frac{1840}{18x180x65} = 9$	
Offsite Home S.W. of Plant	3.6	F	2	30	$X = \frac{1840}{6x120x30} = 85$	
		D	6	10	$X = \frac{1840}{18x250x75} = 5$	

UF_6 Release Prevention and Protection

Frequent surveys for alpha contamination on work area surfaces, continuous air monitoring in potential leak areas, employee urinalyses and medical examinations all contribute substantially to prompt repair of minor leaks and diligent use of protective clothing and masks by operators and maintenance men.

Major effort has been applied to prevent leakage from cylinders of liquid UF_6.

1. A mandatory five-day cooling period assures that UF_6 cylinder contents will be solidified before the cylinders are shipped from the plant or between facilities within the plant.

2. Cylinders of UF_6 are always heated, lifted, moved and stored with the valve in the 12 o'clock position.

3. The integrity of the valve is checked each time before cylinders are filled and a new valve is installed if there is any sign of leakage.

4. Only heavy wall cylinders are used except for the tails cylinders for storage which are not heated for sampling.

5. Each cylinder is pressure tested at least each five years to 400 psig--twice the working pressure.

6. Each cylinder has a steel skirt to protect the valve.

7. A coupling with NGT threads for valve insertion provides maximum thread engagement and the valve is torqued into the cylinder coupling with not more than 400 foot pounds.

8. The cylinders have certified internal volumes and reevaluated fill limits which are based on 250°F UF_6 temperature with five percent safety factor.

9. Cylinder scales are tested daily with certified checkweight cylinders.

10. Cylinder pressure is continuously recorded during the steam heating cycle. Pressure switch instrumentation is provided to close the steam valve and interrupt the heat supply to the cylinder if the cylinder pressure becomes excessive.

11. Conductivity cells in the steam heated vaporizers provide early detection of even minor UF_6 leaks.

Action Points Defined

Action points are guide posts for emergency action based on indications of the magnitude, intensity or scope of the emergency. Action points are defined by numerical values when practical to assure consistent emergency action. For instance, a radiation alarm instrument can be set to initiate evacuation of personnel when the instrument has received a predetermined dose of penetrating radiation. Alpha sensitive instruments or smoke detection type devices can be and sometimes are used to establish action points in a UF_6 release situation, usually for reentry or release from certain protective equipment requirements. Emergency action is usually initiated by other indications. UF_6 reacts with atmospheric moisture to produce a highly visible white cloud of UO_2F_2 and HF hydrates and untenably odorous and corrosive HF gas. The white smoke, acrid smell and knowledge about the source of a UF_6 release will usually be more useful guides for emergency action than instrument indications.

Action Points

Indication	Action
1. 2 alpha counts/min/ft^3) .15 mg/m^3 in air) equivalents $\leq$50 c/min/100 cm^2 transferable alpha surface contamination. No UF_6 or HF smell or smoke	PAL values - No emergency action. Personnel may reenter building where large release has occurred without respiratory protection after decontamination to these levels.

Action Points (cont'd)

	Indication	Action
2.	5-20 c/min/ft^{3}m Wisp of smoke, slight smell.	Operators wear respiratory protection, at least cartridge type respirator, to valve off, tighten connection, etc. Position flexible vacuum hose to pull smoke through UF_6 traps.
3.	20 - 200 c/min/ft^3 Objects in lighted room visible through fog.	If leak cannot be immediately stopped or pulled off through the vacuum system, operators wear full face mask for leak stopping operations. All others evacuate.
4.	$>$ 200 c/min/ft^3 Dense opaque white cloud.	If leak cannot be immediately stopped or pulled to the vacuum system, operators evacuate and pull fire alarm box to summon emergency forces to help dress people in impermeable suits and self-contained breathing masks for leak stopping operations. Operators close building doors as they evacuate to contain the UF_6 in the building. A roof vent or opening high in the building should be open to exhaust displaced air and HF gas.
5.	White cloud escapes building and approaches occupied plant building.	Evacuate building only if there is ample time to get the occupants safely out of the path of the cloud and into vehicles or a safer building. Personnel must not be evacuated into a concentrated contaminant cloud, or into the open imminently threatened by its approach, without respiratory protecti

Action Points (cont'd)

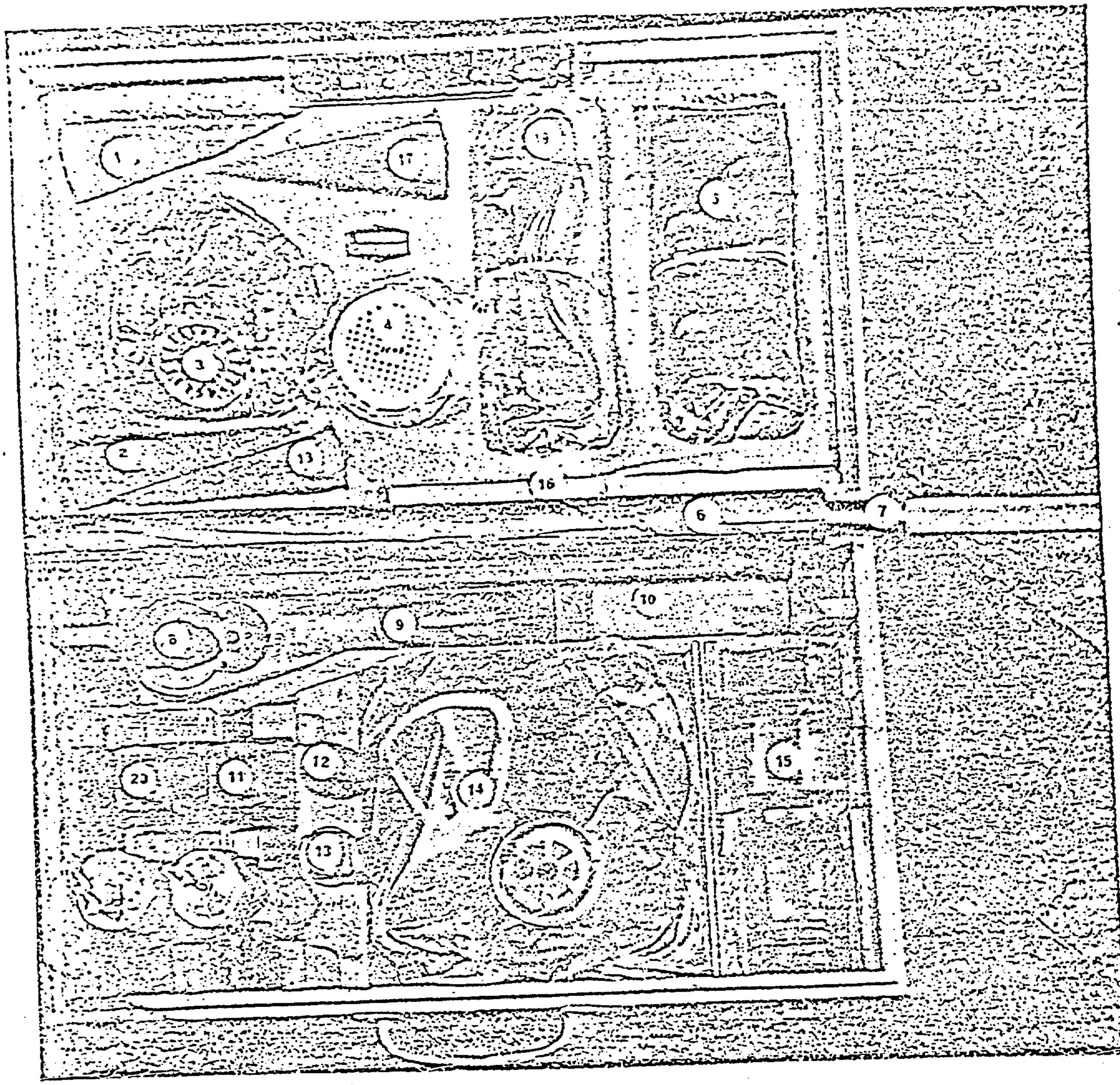
Indication	Action
	The emergency director will dispatch emergency squad men to assist occupants of imminently threatened buildings to close windows and doors and shut down ventilating and air conditioning systems to make the building a safe refuge. Emergency squad men in the building will be in radio contact with the emergency director, who from his up-wind position, can watch the behavior of the contaminant cloud and determine the best time and route if evacuation is necessary. If the contaminant cloud persists around the occupied building, it may be necessa[ry] for emergency squad men to provide masks and coveralls and to effect the building evacuation in groups as large as the available supply of masks which can be r[e]used by succeeding evacuating groups.
6. White cloud from large leak from hot cylinder leaves plant perimeter. Meteorological conditions cause cloud to rise well above ground level.	Plant guards park patrol cars at road intersections at safe distance on both sides of cloud. Plant Protection Office[r] will order traffic stopped and rerouted if cloud approaches road level. Notify patrol. AEC will notify, as appropriate Oak Ridge police or Roane County sheriff Emergency squad members try to keep clou[d] front in sight to warn people if the clo[ud] should strike an inversion and approach ground level.

Action Points (cont'd)

	Indication	Action
7.	Same as 6 except that the contaminant cloud stays near ground level as it leaves the plant area.	Set roadblocks on both sides of clou Notify AEC patrol. AEC will notify, as appropriate, Oak Ridge police or Roane County sheriff. Emergency squ members travel in advance of the clo front to warn people to evacuate the homes and telephone neighbors to do wise. The plant emergency director direct the offsite activities until is relieved by an official of AEC or local law officer.
8.	Personnel are exposed to UF_6 gas or the contaminant cloud. Exposure is slight, no breathing difficulty or skin burn.	Everyone who thinks he may have brea any of the contaminated air or is kn to have been in the contaminant clou will be provided with labeled urine sample bottles and instructions. Me will follow up on alpha positive sa
9.	Exposed personnel have some sign of respiratory congestion or other positive evidence of exposure or skin burn.	Exposed personnel will be transport to a doctor as soon as practical. Oxygen will be administered as soon possible to people with breathing di ficulty. Skin burns will be washed water.

OFF AREA EMERGENCY KIT FOR UF_6 CYLINDERS

PHOTO NO. PH-71-1499



ITEM NO.	EQUIPMENT
1	2-inch wooden peg
2	1-1/2-inch wooden peg
3	Respirator
4	No. 213-100 respirator filter
5	Neoprene gloves
6	1-inch x 18-inch pipe (to increase leverage on valve socket handle)
7	3/4-inch socket wrench handle
8	3/4-inch socket wrench
9	1-inch thread tap
10	13/16-inch extractor
11	1-inch valve
12	1/2-inch socket (to operate 1-inch valve stem)
13	3/4-inch socket (to use on 1-inch tap)
14	Assault mask
15	1-inch valve wrench (to remove Superior valve)
16	Six 10-inch x 10-inch plastic bags (for contaminated items)
17	Spare 2-inch wooden peg
18	Spare 1-1/2-inch wooden peg
19	Spare Neoprene gloves
20	Spare 1-inch Superior valve

UF_6 RELEASE RATES

A study was made to determine approximate leak rate and material loss which might be expected to result if the valve should be broken off a heavy wall fourteen-ton cylinder containing our ORGDP fill limit of 27030 pounds of hot liquid UF_6.

PROBLEM: A steel UF_6 cylinder has a tare weight of 5050 pounds and internal volum 143 cubic feet. It contains 27030 pounds net weight UF_6 and cylinder and contents are at 220°F. The cylinder valve which has a 7/8-inch inside diameter is broken off flush with the outside end of coupling boss (see appended cylinder and valve drawings) leaving a cylindrical opening, 7/8 inches in diameter and one-inch long. Calculate loss and rate of loss of UF_6 from the cylinder (1) valve at bottom—six o'clock position (2) valve in 12 o'clock position.

ASSUMPTIONS: There are no impurities in the UF_6 and UF_6 gas conforms to perfect gas laws. (Recent studies indicate only two or three percent deviation in our range of interest.) Also assume no significant amount of external heating or cooling after the valve break—consider only the heat contribution from the hot UF_6 and cylinder.

DISCUSSION: The effect of impurities in the cylinder such as HF or air would be to increase the pressure in the gas volume which might greatly increase the liqui expubion rate—problem (1). However, the effect of dilution should actually decrease the rate of loss of UF_6 in a gas phase leak; but, the increased pressure might make it more difficult to stop the leakage.

Calculations show that with the valve at 6 o'clock all of the liquid UF_6 would be discharged from the cylinder in about 15 minutes.

With the valve in the 12 o'clock position the leak down to atmospheric pressure c best be analyzed in three stages: (1) Leak down from 220°F and 67 psia to the triple point 147.3°F and 22 psia. (2) Evaporation and sublimation at constant triple point temperature and pressure until all of the liquid has frozen to solid (3) Final sublimation of the solid down to atmospheric pressure at 133°F and 14.7 psia. The pounds of UF_6 lost in each of the three stages can be calculated from the enthalpy curves, heats of vaporization, fusion and sublimation of UF_6 which are appended to this report. Flow rates are calculated for the three stages of leakage using Marks* formula for gas flow through orifices and substituting appropriate values for UF_6. See Figure 1 for details and completed calculations.

SOLUTION

(1) Valve in bottom--6 o'clock position

Escape route for the liquid is a cylindrical tube 7/8-inch diameter and one-inch long. Marks' Handbook* gives the formula for calculating liquid flow through such an orifice or short pipe as follows:

$Q = CA\sqrt{2gh}$ where Q = flow rate in cubic feet per second C is the orifice discharge coefficient which may vary from 0.62 to 0.82 for the type we are considering depending on several factors. We show two calculations to outline the probable flow limits. A = Cross sectional opening of the orifice in square feet and h = liquid head in feet. g is gravitational acceleration constant = 32.2 cubic feet per second /sec.

Since virtually all of the evaporation and cooling of the liquid will take place outside the cylinder the pressure on the surface will correspond to the vapor pressure of UF_6 at 220°F = 67 psia. The head will correspond to 67 - 14.7 = 52.3 psig = 52.3 x 144#/ft^2. One cubic foot of UF_6 liquid at 220°F weighs 211 pounds. Therefore one foot of head = 211#/ft^2 and $h = \frac{52.3 \times 144}{211} = 35.7$ ft.

$A = \pi r^2 = 3.14 \times (7/16)^2/144 = .00417\ ft^2$

1. Let C = .62 $Q = .62 \times .00417 \times \sqrt{64.4 \times \frac{144 \times 52.3}{211}} = .00259 \times \sqrt{2298.62}$

   $Q = .00259 \times 47.94 = 0.124\ ft^3\ sec. =$

   Q = 0.124 x 211 = 26.164#/sec = 1570#/minute

   27000/1570 = 17 minutes to expel all liquid

2. Let C = .82 $Q = .82 \times .00417 \times 47.94 = .164\ ft^3/sec.$

   Q = 34.6/sec = 2076#/minute

   27000/2076 = 13 minutes to expel all liquid

* Mechanical Engineers' Handbook by Lionel S. Marks - Fifth Edition, McGraw-Hill 1951

The liquid UF_6 expelled from a cylinder at 220°F would immediately change to solid and gas since liquid UF_6 cannot exist below 22 psia. Each pound of UF_6 at 220°F contains about 46-1/4 BTU of heat, but a pound of solid UF_6 at 133°F where the vapor pressure is atmospheric pressure contains only about 11-1/2 BTU. The 34-3/4 BTU which each pound of UF_6 must lose between the time it is expelled from the cylinder and the time when the solid fraction lies on the floor with atmospheric vapor pressure is internal and instantly available to vaporize the solid. This means that in the approximate 15 minutes which it takes to expel 27000 pounds of liquid UF_6 at 220°F 27000 x 34-3/4 = 938250 BTU are available and 938250/58.7 = 16000 pounds will vaporize. The remaining 11000 pounds of solid on the floor at 133°F will vaporize more slowly down to room temperature--say 70° with BTU content = 4. In this process the 7-1/2 x 11000 = 82500 BTU would vaporize 82500/58.7 = 140 pounds from internal heat. From this point on the solid would vaporize only as it received heat from an outside source.

The 16000 pounds of UF_6 gas evolved in the first ten to fifteen minutes of the leak would have a density of about 0.8#/ft^3 at atmospheric pressure and would therefore occupy about 20000 cubic feet. If the spill takes place inside a building, about 2000 cfm of air will have to be vented to prevent over pressure and rupture of the building. HF produced by the reaction of UF_6 with steam and atmospheric moisture will also increase the venting requirement.

(2) Figure 1 shows method, calculations and graph for UF_6 gas flows through the 12 o'clock positioned 7/8-inch opening. Flow rates and quantities of UF_6 lost are calculated independently. Using the formula shown in the upper left corner the flow rate at starting conditions of 220°F and 67 psia is found to be 74 pounds per minute. Flow rates are shown at five degree intervals down to 150°F and at the 147.3°F triple point. These points are plotted on the graph on the right side of the chart.

In the right-hand margin of the chart the enthalpy content of liquid UF_6 is shown in BTU per pound. These values are taken from the enthalpy curves for UF_6 appended to this report and are written in the margin at 10°F intervals from 220°F down to 150°F and at the triple point. The off scale 13.2 in the lower right margin indicates enthalpy of solid UF_6 at 147.3°F. For each 10°F drop in temperature from 220° to 150° there is a 1.32 BTU/# loss from the liquid. This is heat available to evaporate UF_6 gas and the amount of gas evolved will be 1.32X pounds of liquid/heat of vaporization. The heat of vaporization was taken from the enthalpy curves for the midpoint of each 10°F interval.

Heat contributed by the cylinder, assuming its temperature stays the same as the liquid, is 5050 x .12(Sp.Ht) x Δ t. And the UF_6 gas vaporized in each of the 10°F intervals by heat from the cylinder is 5050 x .12 x 10 = 6060/heat of vaporization of UF_6 at midpoint of the temperature interval.

Adding the pounds of UF_6 liquid vaporized by heat from the liquid to the pounds of UF_6 liquid vaporized by heat from the cylinder shows 1283 pounds of UF_6 gas will be evolved and escape from the cylinder in the first 10°F interval from 220°F to 210°F. The 1283 pounds is subtracted from the 26980 pounds at the beginning of the leak to get the 25697 pounds which will contribute heat for vaporization during the next 10°F interval. This process is repeated for each 10°F interval down to 150°F, and for the 2.7°F change from 150°F to the triple point.

The time it takes to leak the pounds of UF_6 which are shown to be lost in each 10°F interval is obtained by dividing the pounds lost by the rate of loss at the midpoint of that interval. Adding up the time and pounds shows 7882 pounds lost in 136 minutes in the leakdown from 220°F to the triple point.

At the bottom of Figure 1 it is shown that 7613 pounds of UF_6 gas will be lost in 198 minutes during the constant temperature period while the liquid freezes and another 441 pound loss in 23 minutes during the leakdown to atmosphere pressure. Altogether about 16000 pounds is lost in about 6 hours.

Figure 2 compares the leak rates through a 7/8-inch diameter orifice, which you might have if a valve were broken off, to the leak rate through a 1-1/4" diameter orifice, which you would have if the valve were screwed out of the cylinder. Since amount of material and heat changes are the same, under our assumption of no outside influence, the loss of UF_6 is exactly the same in each stage of the leakdown. Only the leak rate is a little more than twice as great and the leakdown time a little less than half. In actuality the material loss would be a little greater through the 1-1/4" opening because there would be less time to lose heat to the outside and more would be used in vaporizing UF_6.

Figure 3 is the same as Figure 1 except the starting temperature is 200°F instead of 220°F. If allowed to leak down to atmospheric pressure there is only about one thousand pounds difference in the losses. The big advantage of the lower initial temperature is that the lower temperature and pressure and lower leak rate should make it easier and safer to plug the opening and stop the leakag sooner and with less material loss.

CONCLUSIONS

If a valve positioned below the liquid level of UF_6 in a cylinder breaks off, all of the liquid down to the level of the valve will be expelled so quickly and forcefully that it would be impractical and unsafe to try to plug off the flow of hot liquid. Even for small liquid leaks the most practical approach might be to attempt to tilt or roll the cylinder to bring the opening above the liquid level and then attempt to stop the gas leak.

There is enough volume in each of our UF_6 cylinder handling buildings to contain all of the gas which would flash from any cylinder leak of liquid or gaseous UF_6. Venting capacity at or near roof level for HF and displaced air in case of high pressure expulsion of UF_6 liquid may need engineering study.

There should be adequate time to dress out an emergency crew in complete protective clothing and self-contained breathing equipment to safely plug off a gas leak from a broken off valve in the 12 o'clock position before a ton of the gas has escaped from the cylinder. Visibility will be the chief problem inside a building filled with dense white fog. It may be possible to find a path to the cylinder leak by having the emergency crew use a fire hose with fog nozzle to clear the way.

Both dry ice and water may be used on a leaky cylinder to reduce the vapor pressu but care should be used not to introduce a stream of water into a cylinder of U-2 enriched UF_6.

UF_6 LEAK PROCEDURES

SMALL VAPOR LEAKS

Vapor leaks through valve seats, valve packing, faulty gaskets or fittings are usually small enough to be controlled by the local operator. The operator, wearing a respirator, may use a flexible duct to exhaust fumes to the vacuum system while he does the necessary valving to isolate the leak. When the leak is at a cylinder valve and cannot be stopped by tightening seat or packing nut the valve and cylinder may be packed in dry ice. When the cylinder is cold the faulty valve can be removed and a new one installed.

SMALL LIQUID LEAKS

If a liquid leak should develop in a cylinder the best method of control would be to tilt or roll it to bring the leak above the surface of the liquid and then freeze or plug the vapor leak.

LARGE VAPOR LEAKS

Leakage from a hot cylinder of liquid UF_6 with wide open or broken off valve in the 12 o'clock position might exceed a pound per second at pressures more than 50 psig and temperature more than 200°F. Unless the operator can immediately valve off a leak of such magnitude he will necessarily evacuate the building and use radio, telephone or fire alarm to summon help. He will close the door behind him as he leaves and as soon as possible all outside doors and windows will be closed to contain as much as possible of the UF_6 inside the building.

Local and plant emergency directors and squads will assemble just outside the building or close upwind if the cylinder is out-of-doors. In less than ten minutes from the time of the alarm, two or more emergency squad men will be dressed out in acid suits with self-contained breathing masks and thermal protection for hands and arms. At least one of these will be a local squad man completely familiar with the building. Due to the dense opaque fog inside the building they will be unable to see anything and must be guided by feeling with hands and feet and by the loud sound of gas escaping from the cylinder. When the trained men find the cylinder and pinpoint the leak by feeling the outrush of gas with gloved hand they can stop the leak by driving a tapered wood plug into the opening. Limited experience with actual UF_6 leaks and recent experiments with steam at comparable pressures and temperatures prove the practicality of this plugging technique.

While the attempt to plug the leak is in progress, other members of the emergency squad will be procuring blocks of dry ice and tarpaulins to pack around the valve and cylinder. If the leak is from a crack in valve or cylinder which cannot be plugged with the tapered wood dowels, a rubber-lined patch can be held tightly against the crack while clamps or rope or chains are assembled to anchor it more securely. Rubber-lined steel patches contoured to fit the cylinders together with chains and jacks for tightening are available at K-1131 and K-1423.

While attempts to plug a large UF_6 gas release at the source are in progress, the building will be the holding plenum for UF_6 gas. But the buildings are not gas tight and the door will have to be opened temporarily to admit men and materials for stopping the leak at the cylinder. Gas escaping the building near floor level will be mostly UF_6 while that escaping through roof vents will be mostly air and HF. After the cylinder leak has been stopped or attempts to stop it have been abandoned, steam will be admitted to the room to hydrolize the gas and precipitate solid UO_2F_2 which can be vacuumed up for recovery of the uranium.

If the big vapor leak starts while the cylinder is out-of-doors it may be stopped relatively quickly because it can be approached from upwind and the appropriate stopper determined without the visibility handicap of fog inside a room. However, if the leak cannot be quickly stopped the cylinder should be moved inside the building so that the gas can be contained and the uranium recovered.

The use of water to cool a cylinder or knock down fog should usually be avoided not only for the possible criticality hazard but also for economic reasons and pollution control. UO_2F_2 precipitated by steam inside a building is recoverable; that washed into the sewer system usually is not.

LARGE LIQUID LEAKS

UF_6 would be expelled so rapidly and forcefully through an open or broken off valve or similarly large rupture crack below the liquid surface that it could not be safely plugged or stopped. If the cylinder cannot be rolled or tilted to bring the opening above the liquid level all liquid down to the opening will be expelled and fifty to sixty percent of the expelled material will flash to gas during the time it is being expelled from the cylinder. Where a wide open or broken off valve is at the six o'clock position of a full fourteen-ton cylinder as much as sixteen thousand pounds of UF_6 gas would be generated in about fifteen minutes. There is volume enough inside the processing buildings to contain all of the UF_6 if the venting capacity for displaced air and HF near roof level is in the order of two or three thousand cubic feet per minute. Lower level doors and windows must be closed as soon as possible to contain the UF_6.

PLANTWIDE PROCEDURES FOR LARGE UF_6 RELEASES

UF_6 which escapes from a building or a cylinder out-of-doors will react with atmospheric moisture to form a white cloud of HF hydrates and UO_2F_2. In extremely large releases the center of the plume may be nearly clear with high concentrations of unreacted UF_6 and air dried by the leading edges of the release. But there will always be white smoke bordering the lethal concentrations of gas and light over the plant area will aid the emergency director to keep track of the movement of the cloud. One emergency squad man on the K-25 building roof can keep out of the cloud and radio information about its spread and directional changes.

References

(1) Handling Discharge of Heavier-Than-Air Gases From Relief Valves by F. T. Bodurtha, P. A. Palmer, and W. H. Walsh of E. I. du Pont, Wilmington, Delaware for American Institute of Chemical Engineers, Loss Prevention Symposium, New York City, November 27-30, 1972

(2) Bioassay Aspects of a UF_6 Fume Release, M. W. Boback and R. C. Heatherton, National Lead Company of Ohio, 12th Annual Bioassay and Analytical Chemistry Meeting, Gatlinburg, Tennessee, October 13-14, 1966

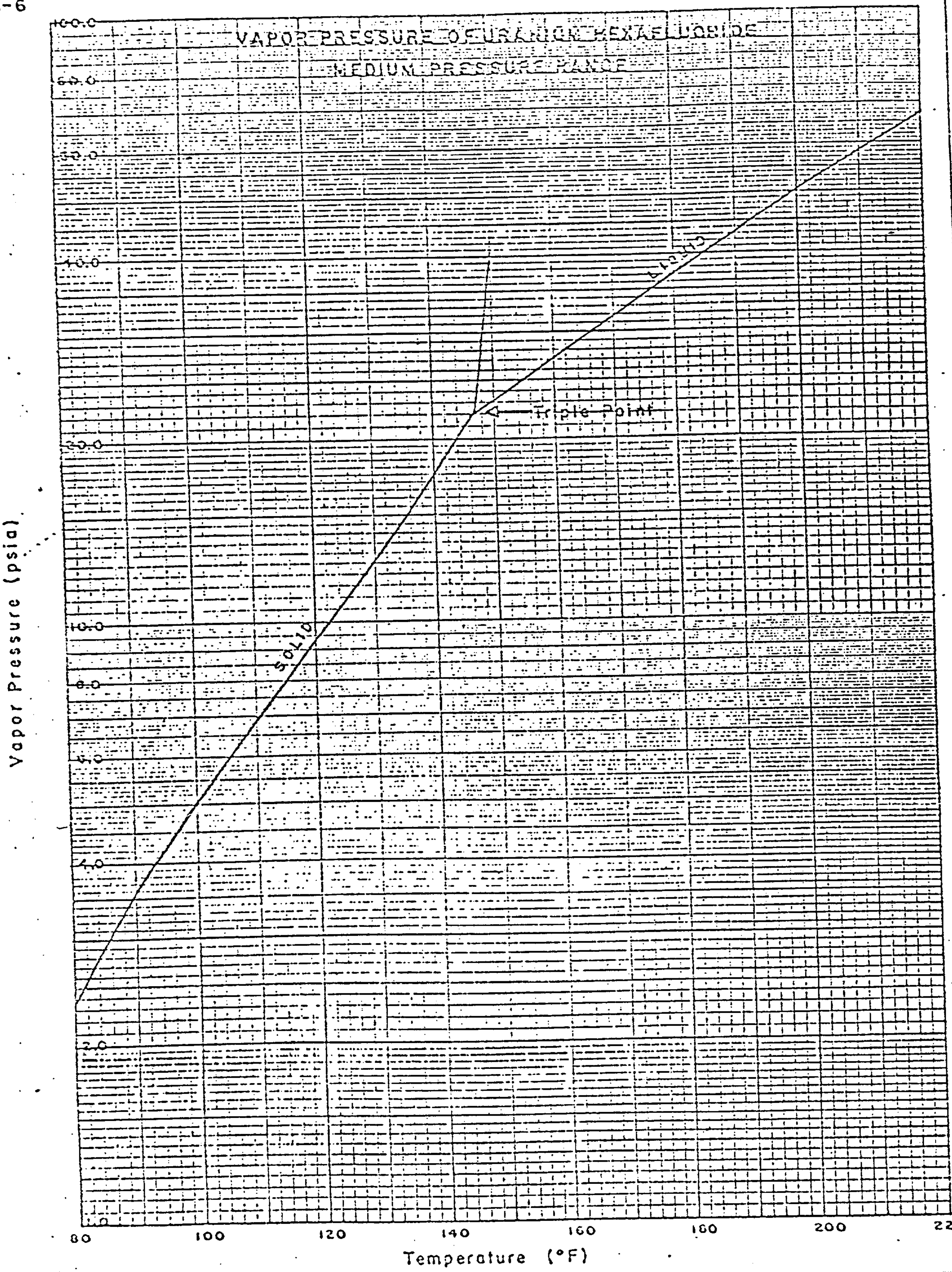
(3) Guides for Short-Term Exposures of the Public to Air Pollutants by The Committee on Toxicology of the National Academy of Sciences - National Research Council, Washington, D. C., August, 1971

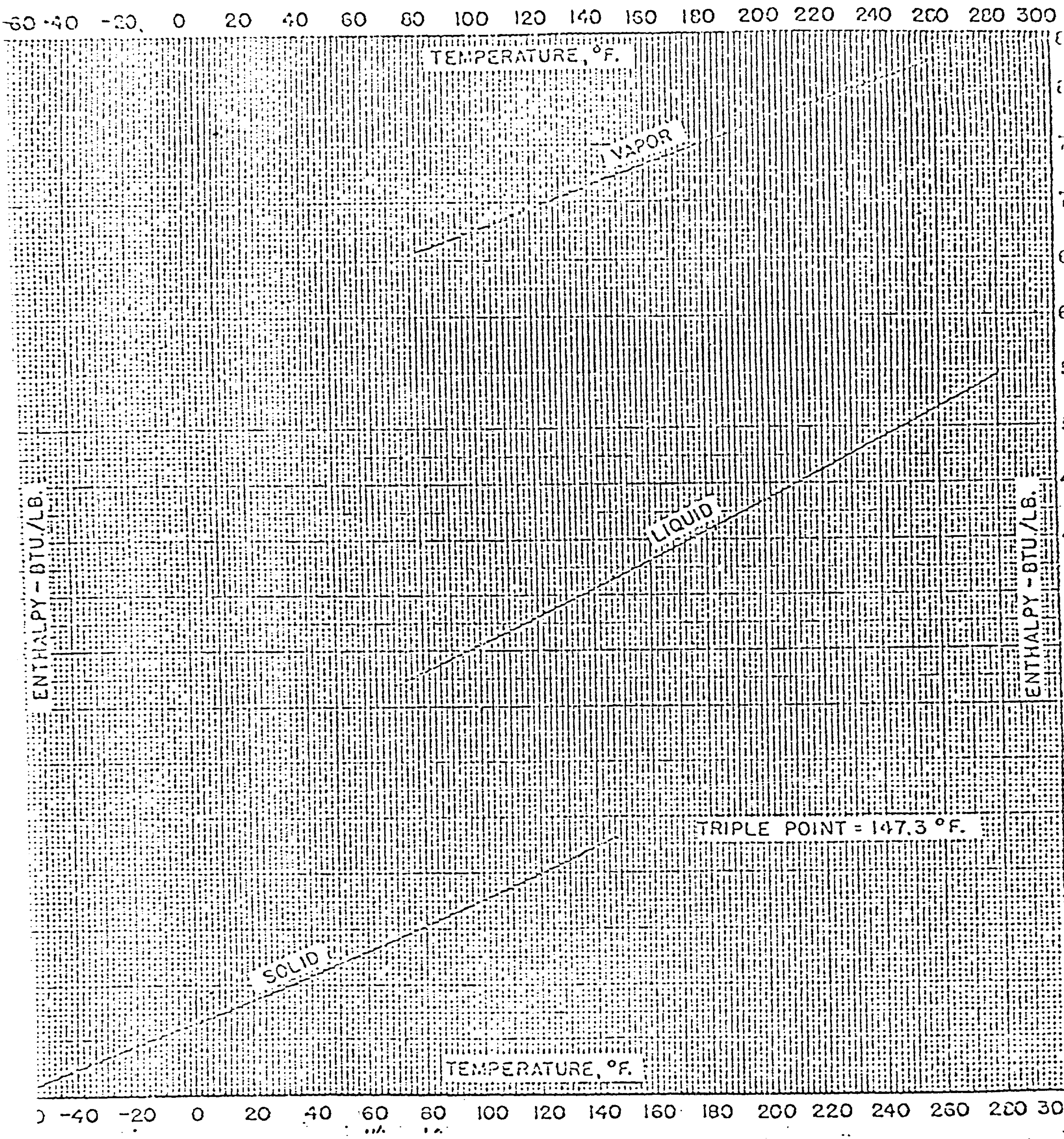
(4) Basis for Establishing Emergency Inhalation Exposure Limits Applicable to Military and Space Chemicals - National Academy of Sciences - National Research Council, 1964

(5) Meteorology and Atomic Energy - 1968, Atomic Energy Commission

GENERAL PROPERTIES OF PROCESS GAS

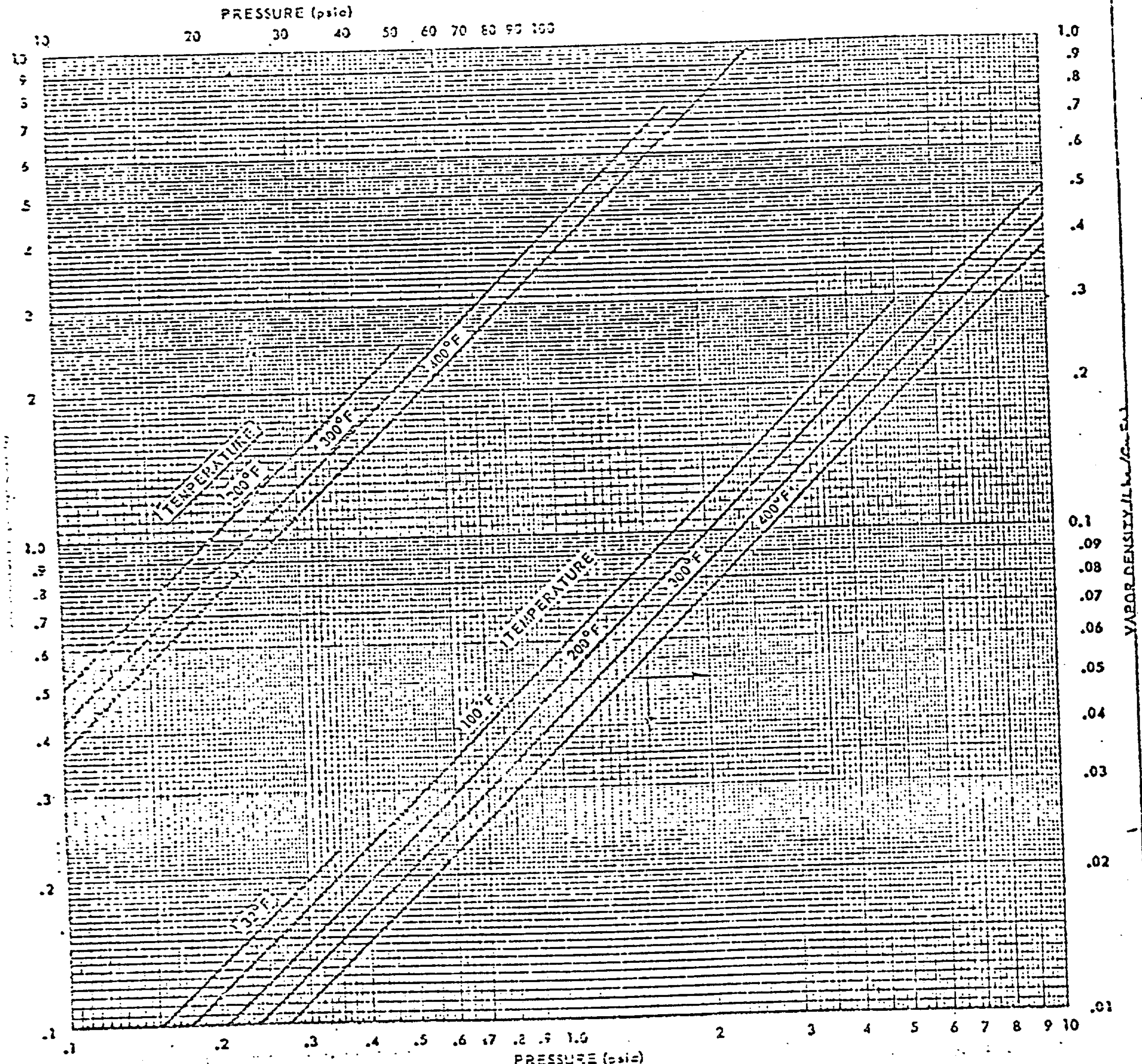
Chemical Name	Uranium Hexafluoride
Chemical Formula	UF_6
Molecular Weight — $U^{235}F_6$	349
$U^{238}F_6$	352
Melting Point	147.3°F 64.1°C
Sublimation Point at 14.7 psia	133.5°F 56.4°C
Vapor pressure at melting point	22.0 psia 1.5 atm.
Density of solid at 68°F	292 lbs./cu. ft. 4.69 gms./c.c.
Critical Temperature	455°F 235°C
Triple point data:	
Temperature	147°F 64°C
Pressure	22 psia 1.5 atm.
Density of Liquid	229 lbs./cu. ft. 3.67 gms./c.c.
C_p/C_v at 140°F	1.067
Heat of Sublimation at 147°F	58.7 BTU/lb. 32.6 cal./gm.
Heat of fusion at 147°F	23.4 BTU/lb. 13.0 cal./gm.
Heat of Vaporization at 147°F	35.3 BTU/lb. 19.6 cal./gm.
Heat of solution in Water at 77°F	258 BTU/lb. 143 cal./gm.


VAPOR PRESSURE OF URANIUM HEXAFLUORIDE
MEDIUM PRESSURE RANGE
Triple Point
SOLID
LIQUID
Vapor Pressure (psia)
100.0
80.0
60.0
40.0
20.0
10.0
8.0
6.0
4.0
2.0
1.0
80
100
120
140
160
180
200
220
Temperature (°F)



-60 -40 -20 0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300
TEMPERATURE, °F.
VAPOR
LIQUID
ENTHALPY – BTU./LB.
ENTHALPY – BTU./LB.
TRIPLE POINT = 147.3 °F.
SOLID
TEMPERATURE, °F.
-40 -20 0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300

DENSITY OF GASEOUS URANIUM HEXAFLUORIDE



A-3 GRAPHICAL AND TABULAR AIDS

The following tables and graphs (Tables A.1 and A.2 and Figs. A.1–A.8) are based either on the Pasquill graphs in the version given by Hilsmeier and Gifford (1962) or on the discussion of instantaneous-source information in Chap. 4. The Pasquill curves can be relabeled in terms of σ_θ as noted in Secs. 4-4.3 and 4-4.4. No account was taken of the effect of a lid to vertical mixing in the construction of the continuous-source graphs. This should be considered as indicated in Sec. 3-3.5.1.2.

Table A.1—RELATION OF PASQUILL TURBULENCE TYPES TO WEATHER CONDITIONS

A—Extremely unstable conditions
B—Moderately unstable conditions
C—Slightly unstable conditions
D—Neutral conditions*
E—Slightly stable conditions
F—Moderately stable conditions

Surface wind speed, m/sec	Daytime insolation: Strong	Daytime insolation: Moderate	Daytime insolation: Slight	Nighttime conditions: Thin overcast or ≥ 4/8 cloudiness†	Nighttime conditions: ≤ 3/8 cloudiness
<2	A	A–B	B		
2	A–B	B	C	E	F
4	B	B–C	C	D	E
6	C	C–D	D	D	D
>6	C	D	D	D	D

*Applicable to heavy overcast, day or night.
†The degree of cloudiness is defined as that fraction of the sky above the local apparent horizon that is covered by clouds.

Table A.2—SUGGESTED VALUES OF σ_{yI}, σ_{zI}, AND $\chi_p\bar{u}/Q$ FOR INSTANTANEOUS RELEASES*†

Parameter	Conditions	Value at 100 m	Value at 4000 m	Approximate power function
σ_{yI}, m	Unstable	10.0	300	$0.14(x)^{0.92}$
	Neutral	4.0	120	$0.06(x)^{0.92}$
	Very stable	1.3	35.0	$0.02(x)^{0.89}$
σ_{zI}, m	Unstable	15.0	220	$0.53(x)^{0.73}$
	Neutral	3.8	50.0	$0.15(x)^{0.70}$
	Very stable	0.75	7.0	$0.05(x)^{0.61}$
$\chi_p\bar{u}/Q$, m^{-2}	Unstable	2.12×10^{-3}	4.81×10^{-6}	$4.20(x)^{-1.65}$
	Neutral	2.05×10^{-2}	5.30×10^{-5}	$35.5(x)^{-1.62}$
	Very stable	3.26×10^{-1}	1.30×10^{-3}	$330.0(x)^{-1.50}$

*See Sec. 4-10.3.
†The power functions are applicable in the given range of distances only.

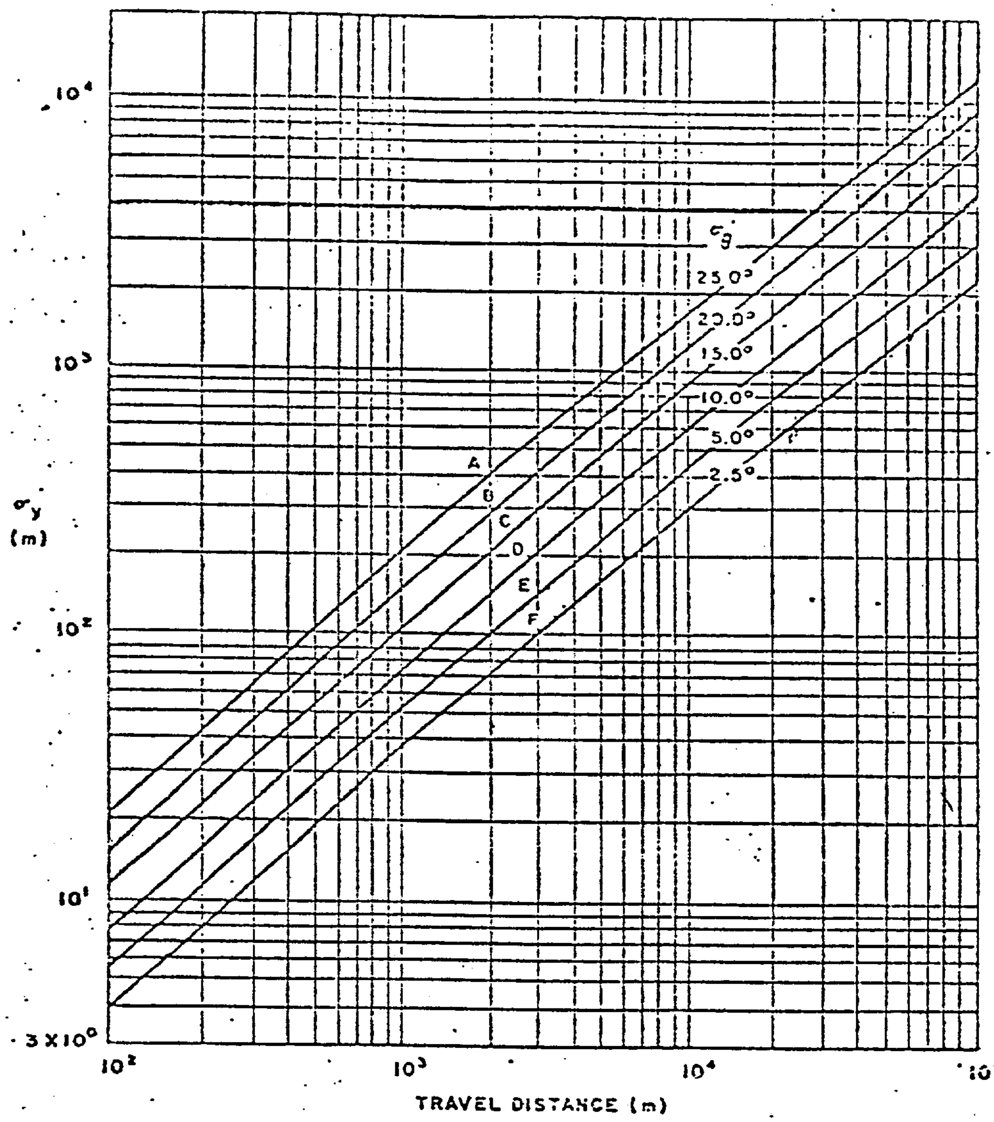


Fig. A.2—Standard deviation of the lateral concentration distribution, σ_y, as a function of travel distance from a continuous source. A–F are Pasquill's diffusion categories.

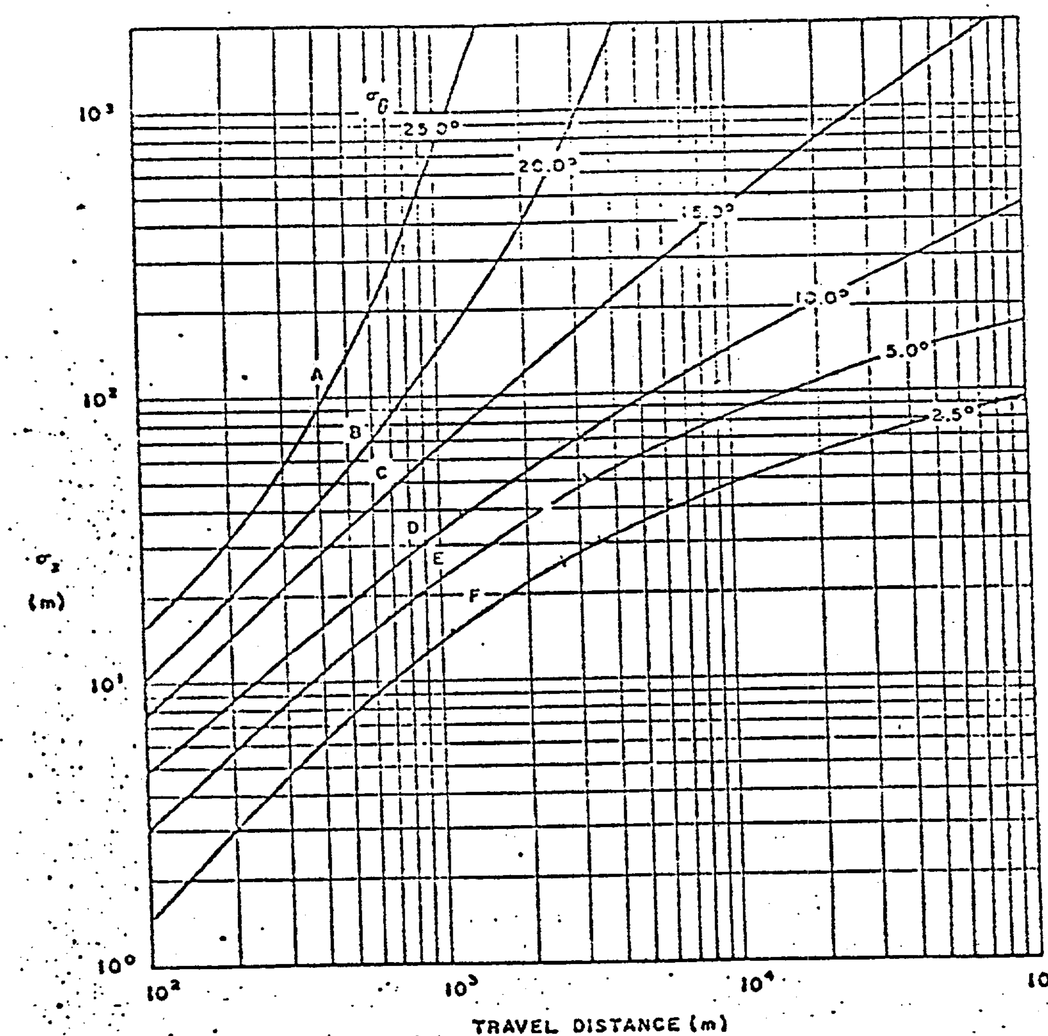


Fig. A.3—Standard deviation of the vertical concentration distribution, σ_z, as a function of travel distance from a continuous source. A–F are Pasquill's diffusion categories.

Figure 3 Same as figure 1
except cylinder is heated only to 200°F

220°F

BTU/#

$\frac{26980 \times 1.32}{34} = 1047\#$ — $1225/64.95 = 18.86$ minutes

$\frac{5050 \times 10 \times .12}{34} = \frac{178}{1225}\#$

$\frac{25755 \times 1.32}{34.2} = 994$ — $1171/60.28 = 19.43$

$\frac{6060}{34.2} = \frac{177}{1171}$

$\frac{24581 \times 1.32}{34.5} = 941$ — $1117/55.18 = 20.24$

$\frac{6060}{34.5} = \frac{176}{1117}$

$\frac{23467 \times 1.32}{35.0} = 885$ — $1058/50.35 = 21.01$

$\frac{6060}{35.0} = \frac{173}{1058}$

$\frac{22409 \times 1.32}{35.2} = 840$ — $1012/43.97 = 23.01$

$\frac{6060}{35.2} = \frac{172}{1012}$

$\frac{21397 \times .4}{36.3} = 241$ — $295/39.5 = 7.47$

$\frac{5050 \times 23 \times .12 \quad 46}{36.3 \quad 295} = 295$

Total Pounds 5878 — 110 minutes = One hour fifty minutes

66.6#/min 200 — 1.32 — 43.
64.95#/min
62.1 — 190 — 1.32 — 42.
60.28#/min
57.7 — 180 — 1.32 — 40.
55.18#/min
52.6 — 170 — 1.32 — 39.
50.35#/min
47.00 — 160 — 1.32 — 38.
43.97#/min
40.58 — 150 — 37.
39.5#/min — 147.3°F — 36
38.52 Triple Point
140°F

26980 − 5878 = 21102# liquid in cylinder at triple point. 21102 × 23.4 = 493787 BTU of freezing
to vaporize 493787/58.7 = 8412# leaving 21102 − 8412 = 12690# solid in cylinder
loss during freezing 8412/38.52 #/min takes 218 minutes. Final leak down to atmosphere
(12690 × 1.5) + (5050 × 14.3 × .12)/58.7 = 472# in $\frac{472}{19}$ = 472/19 = 30 minutes
Total loss = 14,862# Total time = 358 minutes = 6 hours

Flow rate formula

$$W = C A_2 P_2 \sqrt{\frac{2g}{RT_1} \times \frac{K}{K-1} \left(\frac{P_1}{P_2}\right)^{\frac{K-1}{K}} \left[\left(\frac{P_1}{P_2}\right)^{\frac{K-1}{K}} - 1\right]} \Big/ \sqrt{1-\left(\frac{A_2}{A_1}\right)^2 \left(\frac{P_2}{P_1}\right)^{2/K}}$$

W = #/sec. × 60 = #/min.

$\sqrt{1-\left(\frac{A_2}{A_1}\right)^2\left(\frac{P_2}{P_1}\right)^{2/K}} = 1$ because $\frac{A_2}{A_1}$ very small fraction

C = .72 Orifice discharge constant

A_2 = Orifice Cross Section = .00417 ft²

A_1 = Cylinder "

P_2 = 14.7 psia = 2116.8 #/ft²

g = 32.2

R = 1546/352 = 4.39 for UF_6

T_1 = °R = 460°F + °F on UF_6 Vapor pressure curve

K = Cp/Cv = 1.067 for UF_6

P_1 = Cylinder pressure Corresponds to T_1 on curve

$W = .72 \times .00417 \times 2116.8 \sqrt{\frac{64.4}{4.39 \times 680} \times \frac{1.067}{.067} \times \left(\frac{67}{14.7}\right)^{.063} \times \left[\left(\frac{67}{14.7}\right)^{.063} - 1\right]} \Big/ 1$

Solution

T_1	P_1	W
220	67	74.051
215	63	72.584
210	58	70.483
205	54	68.649
200	50	66.596
195	47	64.948
190	43	62.390
185	40	60.279
180	37	57.846
175	34	55.176
170	31.5	52.622
165	29.5	50.351
160	27	47.034
155	25	43.975
150	23	40.381
147.3	22	38.519

= 1.234 #/sec = 74.05 #/min at start

27030 − 50# gas = 26980 # liquid UF_6

$\frac{26980 \times 1.32}{32.5} = 1096$

17.67 1283# $\frac{1283}{72.59} = 17.67$ $\frac{5050 \times 10 \times .12}{32.5} = 187$

26980 − 1283 = 25697

$\frac{25697 \times 1.32}{33} = 1028$
-184
$\overline{1212}$

17.65 1212# $\frac{1212}{68.65} = 17.65$ $\frac{6060}{33} =$

17.64 1146#

17.98 1084#

18.65 1029#

19.34 974#

21.20 932#

5.63 222#

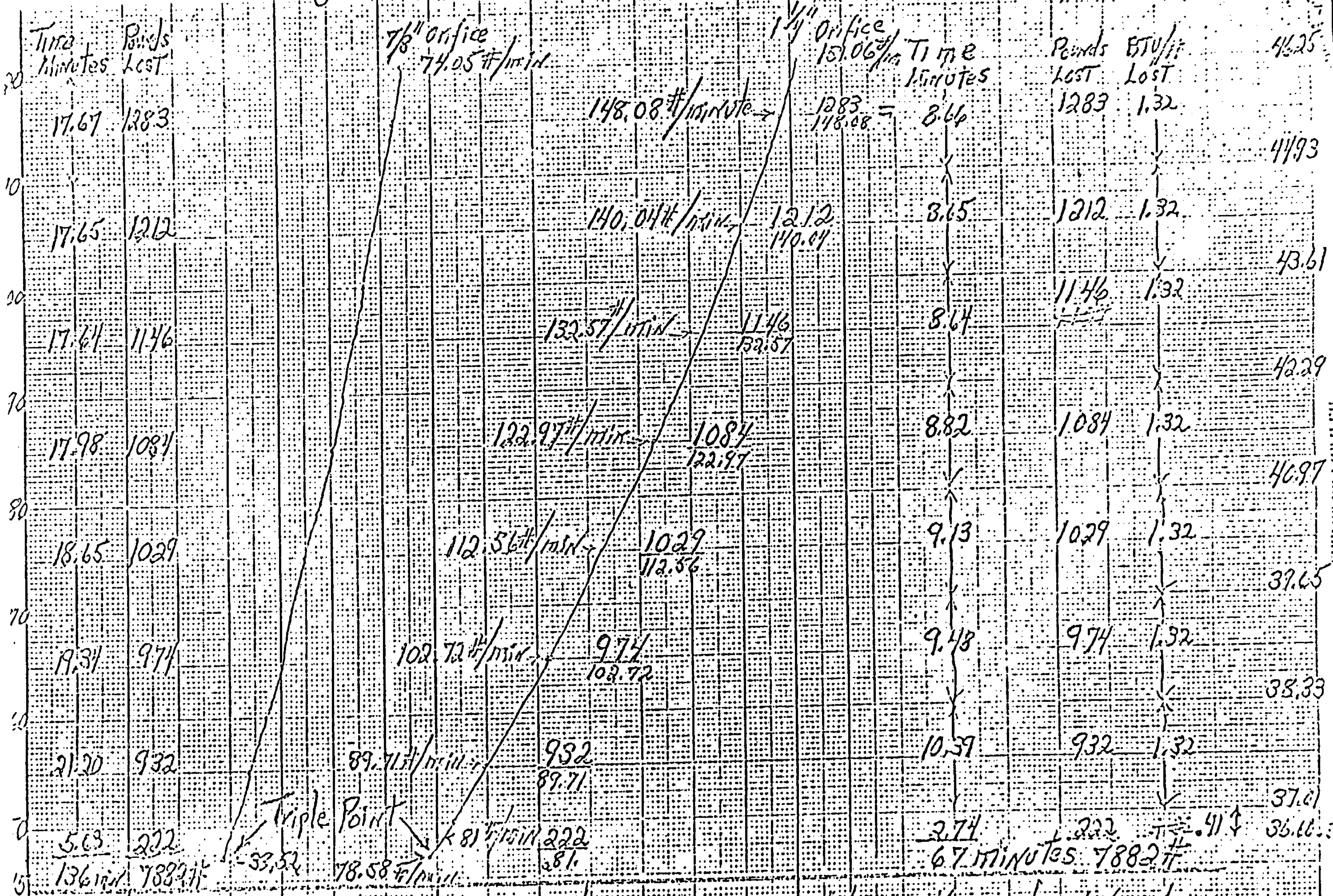
Minutes Total time 136

Total Pounds 7882#   26980 − 7882 = 19098 # at triple pt.

74.05 #/min 220°F
72.59 215
1.32 BTU/# 210
68.65 1.32 205
200
64.95 1.32 195
190
60.28 1.32 185
180
55.18 1.32 175
170
50.35 1.32 165
160
43.97 #/min 1.32 155
150
40.38
39.45 #/min
38.52
0.41 BTU 147.3

Temperature at 147.3°F, Pressure at 22 psia and flow rate at 38.52 #/minute remain constant at triple point until all liquid is frozen, giving up 19098 × 23.4 = 446893 BTU to vaporize 446893/58.7 = 7613 #, leaving 19098 − 7613

23.4 BTU/# Freezing



At triple point temperature & pressure conditions the material loss during freeze-up will be the same 7613# through 7/8 and 1 1/4 inch openings. Only the rate of loss through the 1 1/4" orifice will be greater 7613#/78.55 = 97 minutes instead of 198 and the final 44 psi breakdown will take 11 minutes instead

APPENDIX